Dynamical Downscaling Projections of Late 21st Century Atlantic Hurricane Activity: CMIP3 and CMIP5 Model-based Scenarios

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Abstract.

The robustness of late 21st century dynamical model projections of intense Atlantic hurricane activity is examined. Multi-model ensemble climate change scenarios from CMIP3/A1B and CMIP5/RCP4.5 are compared. Ten individual CMIP3 models are downscaled. Dynamical downscalings are compared from a 18 km grid regional model and a 50 km grid global model. To simulate intense hurricanes, each storm from the regional model is downscaled using the GFDL hurricane model, which has grid spacing as fine as 9 km and ocean coupling.

A significant (p=0.05) reduction in the frequency of tropical storms and hurricanes is projected for both CMIP3 (-23%) and CMIP5 (-27%) ensembles, and by five of ten individual CMIP3 models that were downscaled. However, for strong category 4+ hurricanes (winds >= 65 m s^{-1}), we find a significantly *increased* frequency for the CMIP3 ensemble (+250%); for the CMIP5 ensemble we find a smaller (nonsignificant) increase (+84%). For the frequency of Category 4-5 hurricanes (winds >= 59 m s^{-1}) the Bender et al. (2008) CMIP3-based study had projected a significant increase (+87%); the CMIP5 ensemble projects a smaller (non-significant) increase (+39%). Three of ten individual CMIP3 models show a significant increase in frequency of both Category 4-5 hurricanes and hurricanes stronger than 65 m s^{-1}. Tropical cyclone-related rainfall rates, averaged within 100 km of the storm, increase significantly by 23% (CMIP3) and 14% (CMIP5). The fractional increase in precipitation approximates that expected from water vapor content scaling considerations for relatively large radii (200-400 km), but is substantially higher at relatively smaller radii (50-150 km).

1. Introduction

The influence of global warming as projected for the 21st century by current climate models on hurricane activity in the Atlantic Basin is an important research question. Climate model projections from the Coupled Model Intercomparison Project 3 (CMIP3; Meehl et al. 2007) and Project 5 (CMIP5; Taylor et al. 2012) suggest substantial (~2^{o} C) increases over the century in sea surface temperatures (SSTs) in the basin, while windshear and other storm-influencing factors are projected to change as well (e.g., Vecchi and Soden 2007a,b). Therefore a question arises as to the net impact of these various environmental influences on hurricane activity.

A related issue that arises in attempts to use statistical models to address these issues is the role of local tropical Atlantic SST vs relative SST (that is, tropical Atlantic SST relative to the tropical mean SST) in changing Atlantic hurricane activity. Some statistical relationships linking Atlantic hurricane activity and local tropical Atlantic SSTs suggest a substantial (~2oC) warming of the tropical Atlantic would lead to a large increase (+300%) in a seasonally integrated tropical cyclone power dissipation index (PDI; Emanuel 2005, 2007) (Emanuel 2007; Vecchi et al. 2008). Other statistical and dynamical models and physical considerations (e.g., Latif et al. 2007, Vecchi and Soden 2007a, Swanson 2008, Bender et al. 2010, Zhao et al. 2010, Ramsay and Sobel 2011, Vecchi et al. 2008b, 2011, Villarini et al. 2011, Villarini and Vecchi 2012a) suggest that the relative Atlantic SST is a more robust indicator of Atlantic hurricane activity for the types of climate perturbations relevant for both interannual variability and climate change projections; these alternative models suggest much smaller (+/-60%) changes in Atlantic power dissipation over the coming century (Vecchi et al. 2008; Villarini and Vecchi 2012a).

Recently, Villarini and Vecchi (2012c) provided an updated statistical model projection based on the CMIP5 climate model projections. These new projections include an increase in Atlantic

PDI across all 17 CMIP5 models and three representative concentration pathways (RCPs). Since the number of North Atlantic tropical cyclones is not projected to increase significantly in their analysis (Villarini and Vecchi 2012b), they attribute the increased PDI to an intensification of Atlantic tropical cyclones in response to both greenhouse gas (GHG) increases and aerosol changes over the coming decades with a significant enhancement by non-GHG (primarily aerosol) forcing in the first half of the 21st century.

In a previous series of papers (Knutson et al. 2007; Knutson et al. 2008; Bender et al. 2010), we have explored these issues using dynamical downscaling approaches. The present study is an extension of these earlier studies, comparing projections using CMIP5 climate models to the earlier CMIP3 projections. We present more uncertainty analysis for the CMIP3 projections (Knutson et al. 2008; Bender et al. 2010) by downscaling ten individual CMIP3 models to explore the resultant spread of the ensemble.

We use three different dynamical downscaling models in different combinations to derive our projections. We use a regional 18-km grid atmospheric model (Zetac; Knutson et al. 2007) nested within the NCEP Reanalyses (Kalnay et al. 1996) and explore climate change scenarios by perturbing the reanalyses with climate model projected changes in large-scale circulation and SSTs for the late 21^{st} century (Knutson et al. 2008). We develop alternative projections of changes in Atlantic tropical storms and hurricanes (up to Category 2) for the same climate change scenarios but using a 50 km grid global atmospheric model (HIRAM; Zhao et al. 2009) for the downscaling. We downscale all of the tropical storms from our 18 km grid regional model, on a case-by-case basis, into the GFDL coupled ocean-atmosphere hurricane prediction system (Bender et al. 2010) in order to simulate hurricanes in the most intense part of the hurricane spectrum, which requires higher model resolution to better resolve the storm inner core.

Through these modeling studies we can explore the sensitivity of our projections to different sources of uncertainty, including: uncertainty in the large-scale projected climate changes (i.e., CMIP3 vs CMIP5 multi-model ensemble projections; range of projections among individual CMIP3 models); and uncertainty in downscaling results for a given climate change scenario and model (Zetac regional model vs. HIRAM 50-km grid global model both applied to the same CMIP3 model projections).

2. Model Description

We use several models at various stages of our hurricane downscaling. These include a regional atmospheric model for seasonal Atlantic simulations; and a hurricane prediction model for a further downscaling of the storms in the regional atmospheric model; and several global climate models, which provide projected late 21st century climate change boundary conditions for our climate change perturbation runs. We also compare with the results from a global atmospheric model run for multi-year "time slices" for the present and projected future climate.

a. Zetac Regional Atlantic basin model

For our present climate (control) condition, we simulate 27 seasons (1980-2006; Aug –October season) of Atlantic hurricane activity using an 18-km grid regional atmospheric model designed specifically to simulate Atlantic hurricane seasonal activity (Knutson et al. 2007). The non-hydrostatic model is run without a sub-grid-scale moist convection parameterization, as discussed in Knutson et al. (2007). The model is forced at the lower boundary by observed SSTs and at the horizontal boundaries by NCEP Reanalyses (Kalnay et al. 1996), as described in Knutson et al. (2007, 2008). This model uses interior spectral nudging (on domain zonal and meridional wavenumbers 0-3, with a nudging timescale of 12 h) to maintain the model's large-scale time-evolving solution close to the NCEP Reanalysis throughout the atmosphere. The same nudging time scale is used for all seasons and experiments (control and global warming cases).

For the climate change perturbation runs, the NCEP Reanalysis (i.e., the nudging target) is modified by a seasonally varying climatological change field that includes the projected changes in the SST, and atmospheric temperature, moisture, and winds from either the CMIP3 or CMIP5 climate models; see Section 2.d for a discussion of the methods for computing GCM anomalies. The atmospheric trace gas (CO_2, O_3, etc.) and aerosol concentrations are not perturbed in the Zetac regional model experiments. However, the impact of these forcings is incorporated into the model through the three-dimensional climate change field--which is used as boundary conditions and as a nudging target for the interior of the atmospheric domain.

The Zetac model successfully simulates the observed interannual variability of Atlantic hurricane counts over 1980-2006 (Knutson et al. 2008; Fig. 2) with a correlation coefficient of 0.84, although the trend is about 40% larger than observed. Since our previous study was completed, we have subsequently extended these simulation experiments through 2008. The additional two years substantially over-predict Atlantic hurricane counts (which for the period 1980-2008 leads to a reduction of the correlation to 0.69, and to a linear trend that is about a factor of two larger than observed). We speculate that the increasingly unrealistic trend in these simulations with the inclusion of the most recent years is derived from large (and presumed spurious) negative trends in NCEP reanalysis temperatures, from the upper troposphere to about 100 mb (Vecchi et al. in preparation). Further details on the Zetac model runs and their use in these experiments are provided in Knutson et al. (2007, 2008).

For the climate change runs, the same interannual variability is present as for the control run, as we add a seasonally varying climate change perturbation, which does not change from year to year, onto the NCEP Reanalyses that are used as the nudging target and boundary conditions. This procedure keeps unchanged the largescale interannual to multidecadal variations in the interior as well as the high-frequency weather variability imposed at the model boundaries. This method avoids some difficulties in the direct use of climate model simulations, which have known biases that can distort tropical storm simulations. It further assumes that the atmospheric variability in the large (interior) scales and boundary conditions of our control simulation is also representative of conditions under the global warming scenario. For example, the occurrence frequency and amplitude of ENSO variability is unchanged from the observed (1980-2006) in our climate change runs.

For the individual CMIP3 models, we performed the Zetac model downscaling for only the 13 odd years (1981-2005) in order to save computing resources.

b. GFDL Hurricane Model

Two versions of the GFDL hurricane model are used in this study. These are the same as used for the Bender et al. (2010) study and include the versions used operationally from 2006 through 2012 both at the U.S. National Weather Service (2006-2009) (termed the "GFDL Hurricane Model") and the version (termed the "GFDN Hurricane Model") that has been used by the U.S. Navy.

The model is a triply nested moveable mesh regional atmospheric model coupled to the three-dimensional Princeton Ocean Model (Bender et al. 2007). The 5^{o} latitude by 5^{o} longitude inner nest has a grid spacing of about 9 km, and is automatically relocated to follow the moving tropical cyclone of interest. The ocean coupling provides an important physical process for the simulations, as it allows the tropical cyclone to interact with the ocean and generate a cold wake in the SSTs which can affect intensity. We used the 18-model average three-dimensional ocean structure change from the CMIP3 models to represent the change in ocean temperature stratification in the warmer climate for all of the hurricane model climate change experiments. Preliminary sensitivity experiments showed this model to be relatively insensitive to the details of projected changes in the ocean subsurface temperature profile.

Each individual tropical storm and hurricane case from the Zetac regional model was downscaled using the two versions of the hurricane model. We first identified the time of maximum intensity of the storm in the Zetac model, and then backed up three days from that point to begin the five-day hurricane model integration. This approach tends to preclude looking at integrated storm statistics such as PDI in the hurricane model, since only part of the storm lifetime is simulated. Landfalling statistics are also compromised. We plan to used longer integrations of the hurricane model in future studies, if possible, to address some of these issues.

c. HIRAM C180 global model

To explore the dependence of the tropical storm and hurricane frequency change projections on the model used for downscaling, we compare the Zetac 18-km grid regional model projections to those from a 50-km grid global atmospheric model. This model (termed HIRAM C180) is described in Zhao et al. (2009) and realistically simulates the interannual variability of Atlantic hurricane frequency when forced by observed SSTs alone. Other aspects of the simulations from this atmospheric model are described in Held et al (in prep.) The control run is based on 10 repeating seasonal cycles using the observed climatology of SST and sea ice. The climate warming experiments with this model again include ten repeating seasonal cycles, but use the observed climatology modified by changes to SST and sea ice concentration fields. For the CMIP3 experiments , the changes are based on linear trends (2001-2100) from an ensemble of GCMs (Meehl *et al.* 2007) scaled to a 80-year equivalent amplitude (see Section 2.d), and include an increase in CO_2 to 720 ppm, but no other forcing changes such as aerosols. In the warm climate runs, the non-negligible effect of an increase in CO_2 in isolation, with prescribed SSTs – roughly a 20% reduction in both Atlantic tropical cyclones and hurricanes -- is described in Held and Zhao (2011).

A second multi-model ensemble forcing experiment was performed using the CMIP5 (Taylor *et al.* 2012) models. For the CMIP5 runs with the HIRAM model, all greenhouse gases are modified according to the RCP4.5 scenario. Since both the CMIP3 and CMIP5 sets of model experiments are based on 10-year samples (control and late 21st century) using a repeating season cycle, the runs do not include interannual variations such as ENSO; this procedure differs from that used for the Zetac regional model climate change runs (section 2a).

d. Global climate model projections

We use large scale climate change projections from global climate models as boundary conditions in these downscaling studies. For the HIRAM C180 global model experiments, we use only the change in SST and sea ice concentrations from the global climate models, as well as an increase in CO_2 (CMIP3 runs) or all greenhouse gases (CMIP5 runs). For the Zetac regional model late 21st century experiments, we use changes in SST, SLP, air temperature, relative humidity, and wind velocity to modify the NCEP Reanalysis fields that are used as boundary forcing and as the nudging target for the interior spectral nudging procedure (Section 2a).

For our CMIP3-based experiments with both Zetac and HiRAM-C180, we use either an ensemble average of 18 different CMIP3 models, or individual CMIP3 models. For this study, we tested ten of the 18 individual models. The ten selected models were chosen from among the twelve highest-ranking models according to a multi-variate performance index for 20th century historical forcing runs (Reichler and Kim 2008). Two of the twelve highest-ranking models were not included in our set due to issues with the archived humidity data that is required for our experiments. We did not attempt to test all 18 models for this study due to the computational resource requirements. The ten individual models are shown in Fig. 1. The 18 models for the ensemble are listed in Vecchi and Soden (2007a). For the 18-model ensemble, we used the time average of the years 2081-2100 minus the time average for 2001-2010 (IPCC A1B scenario) as the climate change perturbation. When using individual models, we first computed the linear trend through the model fields for 2001-2100 and then used the difference 2081-2100 minus

2001-2020 of the linear trend projection of the fields, in order to reduce the contamination of the model climate change signal by the models' internal variability (Knutson et al. 2008).

For our CMIP5 experiments, we use data from an 18-model ensemble based on the 4.5Wm^{-2} Representative Concentration Pathway scenario (RCP4.5), see Table 1. Because of differing data requirements for Zetac and HiRAM, and because of limited availability of sea ice concentration data, we were limited to exploring a 13-model ensemble average with HiRAM, while with Zetac we were able to explore the full 18-model ensemble average. With the CMIP5 models anomalies were computed as the difference between years 2081-2100 of the RCP4.5 scenario and 1986-2005 of the historical climate simulations, to explore projected changes from present climate to the late 21st century. We have not yet performed the downscaling procedure on individual climate models from the CMIP5 archive due to computing and time limitations for the present study.

3. Results

a. Storm Frequency changes

1) CMIP3 DOWNSCALING EXPERIMENTS

Figure 1 is used to assess the robustness of late 21st century model projections of tropical storm and hurricane frequency changes from either the Zetac 50-km grid regional model (a-c) or the GFDL hurricane model (d-h). By comparing the results for different models and through statistical significance testing for individual models and the multi-model ensemble climate change, the robustness of results can be better assessed. Results are grouped by intensity class of storm with the weakest intensity criterion storms (all storm of at least tropical storm intensity, maximum surface winds of at least 17 m/sec) shown at the top and the most intense storms at the bottom of the figure.

A striking feature of Fig. 1 is the preponderance of negative changes in the warmer climate (reduced frequency) for weaker storms, which then shifts systematically to a preponderance of positive change (increased frequency) for the strongest storms (e.g., Category 4-5 storms with winds of at least 59 m s^{-1} or strong category 4+ storms with winds exceeding 65 m s^{-1}).

Tables 2 and 3 summarize these projected changes, comparing the years 2081-2100 (warm climate) vs. 2001-2020. (Table 3 shows results for the 18-model CMIP3 ensemble based on all years, whereas Table 2 shows the results based on only the odd years, so for the ensemble climate change, the Table 3 (all years) result is emphasized here.) For the CMIP3 ensemble mean climate change projection, the Zetac regional model simulates a significant (p=0.05) 27% reduction (all years) in tropical storm frequency with a range across 10 individual CMIP3 models of -52% to +8% (odd years), with five of ten individual models showing a significant decrease. The average of the 10 individual models (odd years) is -30%, or comparable to the 18-model average climate change.

For hurricanes in the Zetac model simulation, the 18-model ensemble CMIP3 change is -17% (all years), and -24% (odd years), compared to the 10 individual model average of -25% (odd years). The range across the 10 individual CMIP3 models for hurricane frequency is -66% to +22% with 3 of 10 models showing a significant decrease. There is little significant change in major hurricanes (Category 3-5) for the Zetac model.

For the stronger classes of storms, we focus on results from the GFDL hurricane model downscaling (ensemble of GFDL and GFDN model versions) in Fig. 1 (f-h). The model frequency projections for major hurricanes (Category 3-5) from the GFDL hurricane model are summarized as follows: no significant change for the 18-model ensemble climate change, with a significant decrease for four of ten individual CMIP3 models. The average change for the 10 individual CMIP3 models is -13%, with a range of -88% to +71%.

For Category 4-5 storms, a significant increase in frequency is simulated for the warmer climate: with +87% for the 18-model ensemble mean CMIP3 model climate change (all years), compared with +31% (nonsignificant increase) for the average of the 10 individual CMIP3 models (odd years). For the 10 individual models, the range of Category 4-5 frequency changes is -100% to +210%, with three of the ten model downscalings showing a significant increase.

Strong Category 4+ hurricanes with winds exceeding 65 m s^{-1} occur about once per decade in the control run compared with about once every two years in observations (Tables 2, 3). The 18-model ensemble mean CMIP3 frequency (all years) increases significantly by +250%; the change for the average of the 10 individual CMIP3 models is +90% but not statistically significant. The ten individual models have a range of -100% to +480%, with three of ten individual models showing a significant increase. The Atlantic basin power dissipation index (PDI) and U.S. landfalling tropical storm counts and hurricane counts all show a strong tendency for decreases (Table 2, 3), as expected based on the basin-wide changes in the various hurricane categories.

As an alternative to the second dynamical downscaling step, we also tested the statistical adjustment for hurricane intensity developed by Zhao and Held (2010) applied directly to the

Zetac regional model data. This statistical adjustment is based on matching the percentiles of the model control run distribution to the observed wind speed distribution, which substantially lowers the wind speed threshold used to identify higher-category of hurricanes in the model. This approach (Fig. 2) leads to rather similar overall behavior to that seen using the GFDL hurricane model downscaling (Fig. 1) with a preponderance of negative frequency changes for tropical storms and hurricanes, but a preponderance of positive frequency changes for the strongest class of storm examined here (>65 m s^{-1}). However, the increases for the higher intensity storms are not as robust statistically as those obtained from the dynamical downscaling.

The model downscaling frequency projections for tropical storms and hurricanes can also be compared between the Zetac regional model and the Atlantic basin projections obtained the GFDL HIRAM C180 global climate model. The comparison is done (Fig. 3) for the subset of CMIP models that is common to the experiments done with these models. (The C180 model (50-km grid) uses prescribed SST changes from the CMIP models. In contrast, the Zetac model is additionally forced by atmospheric temperature, wind, and moisture changes; these are internally generated by the C180 model.) The 18-model ensemble and seven of the 10 individual models were in common among the downscaling experiments completed thus far using these two downscaling models.

A scatter plot (Fig. 3) summarizes the C180 / Zetac comparison. For tropical storms, in C180 experiments, all seven individual CMIP3 models and the 18-model ensemble climate change show reduced frequency, compared to the Zetac experiments, where six of seven individual models and the 18-model ensemble show a decrease. The correlation between the seven individual CMIP3 model percent change results is 0.77. For hurricanes, five of seven individual CMIP3 models and the 18-model ensemble yield a decrease in frequency using C180, while four of seven individual models plus the 18-model ensemble show a decrease in frequency for Zetac. If we look for consistency of hurricane downscaling response for individual CMIP3 models, only one of the seven models shows an increase in hurricane frequency in both the C180 and Zetac downscaling experiments (upper right quadrant) while three show a decrease in both (lower left quadrant). Still the correlation among the individual model percent change values is 0.73 for the hurricane changes.

2) CMIP5 VS. CMIP3 RESULTS

As an early test of the robustness of our results to the use of the new CMIP5 climate models, we have tested an 18-model ensemble climate change scenario (late 21st century; RCP4.5 emission scenarios). We have not yet had the opportunity to run individual climate model downscalings for the CMIP5 models. The ensemble results are summarized and compared graphically in Figs. 1 and 2, and summarized in tabular form in Table 3. Fig. 1 shows that the basic result from CMIP3 of a significant decrease in the frequency of tropical storms and hurricanes, is reproduced using the independent CMIP5 climate change scenarios. In terms of quantitative comparison (Table 3), the tropical storm frequency change from the Zetac regional model is -27% for CMIP3 compared with -23% for CMIP5 (see also Fig. 3). For hurricane frequency, the Zetac regional model change is -17% for CMIP3 vs. -19% for CMIP5. For U.S. landfalling tropical storms, the projected change is -17% in CMIP3 compared with a +3% change for CMIP5; for U.S. landfalling hurricanes, the projected changes are -23% for CMIP3 and -12% for CMIP5.

For the frequency of major hurricanes (Category 3-5), the 18-model ensemble results show a nominally negative change for both CMIP3 (-17%) and CMIP5 (-16%) but in neither case is this change statistically significant.   Similar magnitude of changes area simulated for PDI (-17% for CMIP3 and -20% for CMIP5).

For the frequency of the most intense hurricanes, the changes shift from negative to at least nominally positive for the CMIP5. For the Category 4-5 hurricanes and hurricanes with winds of at least 65 m s^{-1}, the downscaling framework simulates nominal increases of frequency (+39% and +88) for the CMIP5 model ensemble, however, neither of these changes is not statistically significant. This contrasts with the large and significant increases for the CMIP3 18-model ensemble (+87% for Category 4-5 storms and +250% for hurricanes with winds exceeding 65 m s^{-1}. U.S. landfalling statistics are not presented for the stronger systems owing to the fact that the higher (Category 4-5) storms are only simulated explicitly with the GFDL hurricane model, and those runs, which by design are limited to 5-day duration beginning 3 days prior to maximum intensity in the host (Zetac) model, are not well suited for examination of U.S. landfall frequency. In fact, landfall often did not occur within the 5-day timeframe of the storm experiment even in cases where a landfall eventually did occur in the (host) Zetac model.

b) Storm intensity changes

1) CMIP3 INTENSITY RESULTS

The changes to the hurricane characteristics with climate warming can also be examined in terms of frequency histograms of maximum wind speeds (one value per storm) are shown in Figs. 4 and 5. The Zetac model histograms in Fig. 4 show the clear deficiency of the Zetac model (present day “Control” simulation) at simulating the observed distribution at the high intensity end. This shortcoming has largely motivated our use of the GFDL hurricane model for this study. The higher resolution hurricane model has a more realistic distribution of storm intensities, particularly above 50 m/s (Fig. 5), although it is still deficient at simulating the observed numbers of highest intensity storms (Tables 2, 3).

There is considerable spread in the climate change experiment results among the different models as shown in these figures, yet it is possible to see the common tendency of fewer storms overall in the warm climate runs than in the control runs. While this reduction holds at most intensities, the tendency reverses to one of greater occurrence of storms at the high intensity end in the warmer climate--at least most of the individual models. This amounts to a change in the shape of the normalized histogram such that the distribution becomes slightly flatter and more spread out. These features are also evident in the results for the higher resolution GFDL hurricane model (Fig. 5). However, the consistency of the response of the higher intensity storms is easier to discern in the earlier figure (e.g., Fig. 1) that focuses on the frequency of particular categories of storms, thus allowing for a particular focus on the higher-intensity storms. Although such intense storms are relatively rare in observations compared to the typical hurricanes, and so they tend to be de-emphasized in intensity histograms that depict the entire intensity distribution, (e.g,, Figs. 4 and 5), they nonetheless have important implications for hurricane damage potential. For example, Pielke et al. (2008) conclude that Category 4-5 hurricanes were responsible for nearly half of historical U.S. hurricane damage even though they account for only about 15% of U.S. landfalling tropical cyclones.

2) CMIP 5 VS. CMIP3 INTENSITY RESULTS

The ensemble results for CMIP3 vs. CMIP5, shown in Fig. 6, also illustrate the “flattening” and spreading out of the histogram, as the frequency overall is reduced. That is, the high intensity end of the distribution behaves differently from the middle of the distribution, as it shows an increase in frequency despite the overall reduction in number of storms. This feature is present for both CMIP3 and CMIP5, though it is less apparent for the CMIP5 due to the smaller (statistically nonsignificant) change projected for the frequency of the strongest hurricanes using the CMIP5 ensemble.

An alternate way of assessing intensity changes is to examine the average of the maximum intensities for all storms above certain threshold intensities. Table 3 shows that the mean maximum wind of all tropical storms and hurricanes combined increases about 3% for Zetac runs (CMIP3 and CMIP5) but has a slight decrease (-0.7%) for GFDL hurricane model runs for CMIP3, with a small increase (+1.6%) for CMIP5. For maximum winds of hurricanes (winds of at least 33 m s^{-1}), the results are similar, ranging from -2% to +4%, although there is little relation to the results for tropical storm in terms of which combination of model shows an increase or decrease. In short, the projected changes of mean intensities are relatively small, with a positive tendency in these experiments. The results for the individual models (shown in Table 2) are similar, though with a wider range among the experiments. Note that since only half of the seasons (odd years only) were run for the individual model cases it is perhaps not surprising that the signals are more difficult to discern, owing to the lower expected signal to noise ratio.

c) Storm track and occurrence changes

We present here some limited analysis of changes in the geographical distribution of storm tracks. We focus on the Category 4-5 results for the CMIP3 and CMIP5 ensemble climate change experiments using the GFDL hurricane model. Tracks for the GFDL hurricane model for category 4-5 storms obtained from the GFDL/NWS version are shown on the left column of Fig. 7, while and those for the GFDN version are shown on the right column; results are compared from the CMIP3 and CMIP5 ensemble runs. Note that the increase in frequency of Category 4-5 storms is statistically significant (p=0.05) for the CMIP3 ensemble but not for the CMIP5 ensemble. Nonetheless, it is of interest to compare the track maps for the Category 4-5 storms for the various ensembles. The tracks show some tendency for a shift in the occurrence of the most intense storms toward the Gulf of Mexico (on average) for the CMIP5 climate change runs in comparison to the CMIP3 climate change runs; in the latter, more such storms are simulated over the open Atlantic, (i.e., further from U.S. landfalling regions).

Occurrence maps (Fig. 8) for Category 4-5 storm changes summarize these changes discussed above. While the CMIP3 ensemble showed the largest increase of frequency in the far western Atlantic, in the CMIP5 ensemble runs an increase in occurrence is more focused toward the eastern Gulf of Mexico. In any case, these differences in regional detail between the CMIP3 and

CMIP5-based results should be viewed with a caution against over-interpretation of such regional scale details of the projections, despite the strong interest regarding the climate impacts at such spatial scales. We have not yet demonstrated that our model is capable of providing useful climate change information on storm activity at these smaller spatial scales**.**

d) Storm-related precipitation rate changes

A robust signal in our experiments is the increase of precipitation rates averaged within the near-storm region. For example, Fig. 9 (a) shows the results for the average precipitation rate within 100 km of the storm center for all tropical storms and hurricanes in the Zetac model experiments, including results for the individual CMIP3 models experiments. This metric includes the entire storm lifetime, which is dominated by time spent over the open ocean. The average change for the CMIP3 18-model ensemble, considering all seasons, is +21%, and for the CMIP5 ensemble the average change is +9% (Table 3), with both being statistically significant. For the ten individual models that we have examined from the CMIP3 ensemble, Table 2 shows that all ten have a positive change in this metric, ranging from +11% to +29%; seven of the ten have statistically significant increases according to the Mann-Whitney-Wilcoxon test. Table 3 shows that the average precipitation rate (100 km radius) for storms of at least hurricane intensity in the Zetac regional model (averaging over all such periods) increases by 23% and 14% for the CMIP3 and CMIP5 ensemble mean climates, respectively. An increase in tropical cyclone precipitation rate was a relatively robust signal among other studies that have explored this metric (see review in Knutson et al. 2010).

Figure 9 (b) compares the precipitation rate changes for CMIP3 and CMIP5 for different averaging radii, varying from 50 km to 400 km. For both sets of experiments, the percentage increase is amplified nearer to the storm, but then asymptotes to about +10% at larger radii (~200-400 km). We can use a simple moisture scaling argument to interpret these results. If we assume that the moisture budget within the near-storm region (within 400 km) of the hurricane is dominated by moisture convergence from the larger environment, then fractional increases in atmospheric moisture content in the warmer atmosphere should lead to similar fractional increases in the moisture convergence and thus the precipitation rate. A representative SST change for our experiments (Aug.-Oct. mean, averaged 10-25^{o}N, 20-80^{o}W) is 1.7^{o}C for CMIP3 and 1.3^{o}C for CMIP5. Assuming a 7% increase in lower tropospheric atmospheric water vapor content per degree Celsius SST change, we then obtain the ~10 % increases as depicted by the dashed lines in Fig. 9 (b) for the CMIP3 and CMIP5 environments. Thus our results show that this scaling argument describes our model precipitation increases fairly well for averaging radii of 200-400 km. However, the more amplified model precipitation response seen at smaller radii (between 50 km and 150 km) does not agree with this simple scaling, suggesting that other processes may play a more important role in the response of the hurricane inner-core precipitation rates.

e) Storm translation speed

We have computed average storm propagation speed statistics from our samples. These are shown in Tables 2 and 3. In Table 2, the results for the odd years indicate that while the average speed increases a few percent on average for the CMIP3 ensemble, the individual model projections are mixed, with downscaling results from six models showing an increase and four a decrease. For CMIP3 and CMIP5 ensembles, considering a full 27-season set (Table 3), the CMIP3 ensemble shows a 2% increase, and the CMIP5 and 3% decrease. In short, there is not a clear consistent signal in the storm propagation speed results overall.

4. Discussion and Conclusions

In this study, we have conducted a large number of numerical experiments aimed at exploring the dependence of Atlantic hurricane activity on projected climate changes as obtained from the CMIP3 and CMIP5 coupled model data archive. We have compared downscaling results for CMIP3 against CMIP5, and the spread of results within a substantial subset (ten models) of the 18 models used to form the CMIP3 ensemble.

We have used two different downscaling models that simulate entire seasons or years of hurricane activity – an 18-km grid regional model and a 50-km grid global model – to examine the robustness of the downscaling step. For these, we focus especially on the simulated frequency of tropical storms and hurricanes, as the interannual variability of these metrics is well-produced by these models. On the other hand, to focus on the most intense hurricanes, we have chosen to perform an additional downscaling step, using two versions of a 9-km grid operational regional nested hurricane prediction model (with ocean coupling). As this model has been developed and refined for operational hurricane prediction use, it is able to simulate more intense systems and more realistic spatial structures of storm features than the lower resolution downscaling models.

There are several findings with varying degrees of robustness emerging from this study. One of the most striking features from the Zetac regional model is the robustness of our simulation of fewer Atlantic tropical storms. The ensemble model change is -27% (CMIP3) to -23% (CMIP5) with a range in individual CMIP3 models of -62% to +8%, with five of ten models showing a statistically significant decrease. For hurricanes in the Zetac model, there is a 17% (CMIP3) to 19% (CMIP5) decrease for the multi-model ensembles, but these are not statistically significant. The range of hurricane frequency results across individual CMIP3 models is -66% to +21%, with three of ten individual models showing a significant decrease. Our results quoted above from the Zetac regional model are rather similar overall to those from the C180 global model (Fig. 3). On the other hand, as shown in a recent review (Knutson et al. 2010), agreement on the sign of the projected change of Atlantic tropical storm frequency results is not robust when one considers other published studies. Examples of studies which project at least nominally positive changes in Atlantic tropical storm counts include Sugi et al. (2002); Oouchi et al. (2006); Chauvin et al. (2006; one of two models); Emanuel et al. (2008); Sugi et al. (2009; six of eight experiments); and Murakami et al. (2011; one of three multi-model ensemble experiments). Further insight on the differences in model projections can be gained by replotting the results of these studies in a scatterplot against a statistical model downscale (Villarini et al. 2011) based on the relative SST change used or computed in each dynamical model simulation (Fig. 10). The comparison shows that in most cases where the dynamical models projected increased tropical storm frequency, those models were usually being forced with or had internally computed, SST warming in the tropical Atlantic that exceeded the tropical mean warming. The variance explained by the statistical downscaling model is 55%. Thus the analysis helps to reconcile the differences between the different published Atlantic tropical storm downscaling studies and our studies.

A second overall robust feature is the transition from a reduction in the overall frequency storms and hurricanes, to an increase in the frequency of the most intense hurricanes. This transition is seen most clearly in the figures examining changes in frequency of different categories of storms (e.g., Fig. 1). The feature is most pronounced in the hurricane model downscaling (Fig. 1), where it is nominally present for both the CMIP3 and CMIP5 ensembles. However, we find that it is only statistically significant in our experiments for the CMIP3 18-model ensemble climate change and for three of the ten individual CMIP3 models (Fig. 1). Although the feature is also present to some degree in the statistically adjusted winds obtained from the Zetac regional model (Fig. 2), those changes are not as robust, in terms of statistical significance, as the dynamical downscaling changes. The contrast between the change of storm frequency for the weak to moderate intensity storms compared to that for very intense storms is one of the most robust intensity-related features in our simulations.

While the very intense storms are relatively rare, their importance is considerable. For example, Mendelsohn et al. (2012) note: “With the present climate, almost 93% of tropical cyclone damage is caused by only 10% of the storms.” Of even greater relevance to our results is an analysis of U.S. hurricane damage statistics partitioned by storm category (Pielke et al. 2008). They conclude that Category 4-5 hurricanes were responsible for nearly half of historical U.S.

hurricane damage even though they account for only about 15% of U.S. landfalling tropical cyclones. Clearly, the strongest tropical cyclones have a disproportionate impact on society in terms of storm damage.

A final robust feature of our simulations is the increase in storm-related precipitation rates, which is significant in the CMIP3 and CMIP5 ensemble results and for most of the individual CMIP3 models examined. While the fractional rate of increase varies for different averaging radii (e.g., Fig. 9 b), our results show that the composite hurricane precipitation rate increases robustly in the warm climate simulations using the Zetac regional model. The ensemble increase in near-hurricane precipitation rates for 100 km averaging radius is +23% for the CMIP3 18-model ensemble and +14% for the CMIP5 ensemble. Considering tropical storm-related precipitation rates, all ten individual CMIP3 models show a positive change, ranging from +11% to +29%. A common feature of the CMIP3 and CMIP5 hurricane precipitation results is the amplification of the fractional change in regions relatively close to the storm (roughly 50-150km). At relatively larger averaging radii (roughly 200-400 km), the model results appear to asymptote to change levels close to what would be expected from simple Clausius-Clapeyron atmospheric water vapor scaling arguments. Our precipitation results are consistent with and provide further support for results in a recent review of tropical cyclone climate change simulation studies (Knutson et al. 2010).

A notable change relative to our previously published work is that the CMIP5/RCP4.5 ensemble climate change projections (2081-2100 vs 2001-2020), when downscaled, lead to a (statistically non-significant) 39% increase trend in the frequency of Category 4-5 hurricanes as compared to a statistically significant 87% increase in this metric for the CMIP3/A1B ensemble (Bender et al. 2010). Climate changes from three of the ten individual CMIP3 models (odd years only), lead to a significant increase in the projected number of Category 4-5 storms in our downscaling studies, with a range across ten individual models of -100% to +210%. Our results for high intensity storms can also be compared with those of Murakami et al. (2012), who used a high-resolution global model but reported Category 5 storm results also for the Atlantic basin (auxiliary information provided by Dr. H. Murakami, personal communication, 2011). Their model projects a non-significant increase in category 4-5 storm days in the Atlantic basin (+15 percent) and globally (+4 percent). For category 5 storm days, their model projects significant increases (+56 percent globally, and +290 percent in the Atlantic basin). There are several important caveats to the results from the various models. For example, the Bender et al. model has a substantial (~50 percent) low bias in their simulation of Atlantic category 4-5 hurricane frequency under present climate conditions. Murakami et al. report a relatively small bias in their present-day simulation of Atlantic category 5 storm days, but a large positive bias (almost a factor of 4) in their simulation of Atlantic category 4-5 storm days. In addition, the global model used by Murakami et al. does not include an interactive ocean component, in contrast to the present study and Bender et al. (2010).

The low bias in category 4-5 storm frequency in our model is a limitation of our modeling system in the context of this paper and Bender et al. (2010). However, we not aware of any other dynamical modeling study to date that produces a more realistic simulation of Atlantic category 4-5 frequency, including the multidecadal variation of storm intensity (Bender et al 2010, their Fig. 1 a-d). Our judgment is that the intensity distribution in our model is realistic enough at the category 4-5 level that we can start to take the frequency projections of these very intense storms seriously. We have chosen to present percent changes in category 4-5 storms rather than absolute changes in numbers--owing to this low bias in our control simulations. It is our judgment that this is an appropriate way to attempt to account for this low bias at the present time. A more satisfying remedy awaits improvements in our model (e.g., increase of resolution to better resolve the storm core and eyewall region) so that the frequency of simulated category 4-5 storms is closer to the observed .

As for hurricanes with winds exceeding 65 m/s (which occur about once per decade in the control run compared with about once every two years in observations), the 18-model ensemble mean CMIP3 change (including all years) is statistically significant (+250%), compared with a (nonsignificant) +84% for the ensemble climate change from the CMIP5 models. The ten individual CMIP3 models (simulating odd years only) yield a range for this metric of -100% to +480%, with three of ten individual models showing a significant increase. Note that the low bias in such storms (about 20% of the observed rate) is even more severe than the ~50% low bias for Category 4-5 storms combined as discussed above. As mentioned above, future plans include possibly re-doing these experiments with a higher resolution version of our hurricane model (6 km inner mesh) that is currently under development, in order to improve on the control simulations of these extreme events. In addition, the statistical significance of some of our results could be enhanced through longer simulations even of the present models.

The percentage change in mean storm intensity is relatively small, with only a slight tendency for an increase (Tables 2, 3). In Knutson et al. (2010), the globally averaged mean intensity of tropical cyclones was assessed as likely to increase with climate warming, although they noted that the uncertainties of such projections were larger for individual basins. In their Table S2 (Intensity Projections), the published intensity projected for the Atlantic basin showed relatively small changes in some studies, ranging even to negative values for some individual models that were analyzed (e.g., Vecchi and Soden 2007). Our current results suggest that the projected change in the shape of the intensity distribution (with fewer tropical storm and hurricanes, but tending toward more of the most intense storms) is a more robust projection from modeling framework than is the sign of change in the mean storm intensity, at least for the Atlantic basin.

Overall, our results add further support to previous studies projecting that anthropogenic warming of the Atlantic basin will lead to future (late 21st century) conditions with fewer tropical storms and hurricanes overall. The projection of more frequent intense hurricanes is statistically significant for the CMIP3 ensemble climate change, but only nominally positive, and not statistically significant, for the CMIP5 ensemble. A robust signal is that hurricanes in the warmer climate are projected to have substantially higher rainfall rates than those in the current climate. The projected hurricane precipitation rate increase by the late 21st century scales roughly with the fractional increase in total precipitable water vapor content (~+11%), particularly at relatively larger radii (200-400 km), but shows larger fractional increases (+20% or more) projected near the hurricane core.

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TABLE 1. Summary of the 18 CMIP5 (Taylor *et al.* 2012) global climate models used in this to create the multi-model anomalies. The final two columns indicate the models for which the required data to create boundary conditions for ZETAC (SST, SLP, air temperature and relative humidity; total 18 models) and HiRAM (SST and sea ice concentration; total 13 models) were available.

Modeling Center (or Group)	Model Name	Used in ZETAC	Used in HiRAM
Canadian Centre for Climate Modelling and Analysis	CanESM2	Y	Y
National Center for Atmospheric Research	CCSM4	Y	
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CM5	Y	Y
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-Mk3.6.0	Y	Y
	FGOALS-g2	Y	Y
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-CM3	Y	Y
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-ESM2G	Y	Y
NOAA Geophysical Fluid Dynamics Laboratory	GFDL-ESM2M	Y	Y
Met Office Hadley Centre	HadGEM2-CC	Y	
Met Office Hadley Centre	HadGEM2-ES	Y	Y
Institut Pierre-Simon Laplace	IPSL-CM5A-LR	Y	
Institut Pierre-Simon Laplace	IPSL-CM5A-MR	Y	

Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5	Y	Y
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM	Y	Y
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM-CHEM	Y	
Max Planck Institute for Meteorology	MPI-ESM-LR	Y	Y
Meteorological Research Institute	MRI-CGCM3	Y	Y
Norwegian Climate Centre	NorESM1-M	Y	Y

Table 2. Statistics from CMIP3-based downscaling experiments for Atlantic tropical storms and hurricanes. These experiments use climate change projections from the CMIP3 18-model ensemble or from 10 individual CMIP3 models. See text for details. “atl_NCEP.bams” refers to our Control or present day simulation. The hurricane model results are for the average of runs using the two model versions (GFDL and GFDN).

Model Key:

```
 A  --->  obs
 B  --->  atl_NCEP.bams
 C  --->  atl_A1B_ens18
 D  --->  atl_A1B_gfdl_cm2.1
 E  --->  atl_A1B_mpi
 F  --->  atl_A1B_hadcm3
 G  --->  atl_A1B_mri
 H  --->  atl_A1B_gfdl-cm2.0
 I  --->  atl_A1B_hadgem1
 J  --->  atl_A1B_miroc-hi
 K  --->  atl_A1B_ccsm3
 L  --->  atl_A1B_ingv
 M  --->  atl_A1B_miroc-med
 N  --->  mean of 10 indiviual models (D-M)
```

ZETAC MODEL

Means	A	B	C	D	E	F	G	H	I	J	K	L	M	N
ts	8.846	11.077	7.462	10.077	6.923	5.308	8.308	11.923	4.231	7.462	8.000	8.615	6.308	7.715
hur	5.538	6.385	4.846	6.615	4.154	2.692	5.462	7.769	2.154	4.385	5.615	5.462	3.769	4.808
mhurw	2.615	0.000	0.000	0.000	0.000	0.000	0.077	0.000	0.000	0.000	0.000	0.000	0.000	0.008
mhurw45	1.462	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hur_w65	0.615	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
pdi	234.095	177.483	127.183	184.850	122.797	67.828	152.890	213.492	55.272	129.189	178.898	142.518	99.538	134.728
maxwnd	39.403	34.069	35.262	35.604	35.180	33.615	35.439	36.118	33.056	34.772	36.864	35.700	34.822	35.117
maxwnd_hur	49.069	38.821	39.445	39.924	40.491	35.992	39.287	39.820	36.114	39.890	39.804	39.468	39.113	38.990
lf_ts	2.231	2.385	1.692	2.385	1.769	1.538	1.538	3.538	1.077	1.692	2.077	2.462	1.538	1.962
lf_hur	1.077	1.538	0.846	1.154	0.769	0.462	0.615	1.615	0.308	0.923	1.077	1.000	0.692	0.862
speed	6.518	6.225	6.348	6.692	6.235	6.591	6.102	6.937	6.488	6.410	5.982	6.138	6.142	6.372
rain_storm		167.182	204.559	210.245	203.091	190.628	213.926	216.398	185.839	211.118	209.837	206.908	204.849	205.284

% Change	A	B	C	D	E	F	G	H	I	J	K	L	M	N

ts		0.000	-32.635	-9.028	-37.501	-52.081	-24.998	7.637	-61.804	-32.635	-27.778	-22.226	-43.053	-30.351
hur		0.000	-24.103	3.602	-34.941	-57.839	-14.456	21.676	-66.265	-31.323	-12.059	-14.456	-40.971	-24.698
mhurw		0.000	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
mhurw45		0.000	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
hur_w65		0.000	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN
pdi		0.000	-28.341	4.151	-30.812	-61.783	-13.857	20.289	-68.858	-27.210	0.797	-19.701	-43.917	-24.090
maxwnd		0.000	3.502	4.506	3.261	-1.333	4.021	6.014	-2.973	2.063	8.204	4.787	2.210	3.076
maxwnd_hur		0.000	1.607	2.841	4.302	-7.287	1.200	2.573	-6.973	2.754	2.532	1.667	0.752	0.435
lf_ts		0.000	-29.057	0.000	-25.828	-35.514	-35.514	48.344	-54.843	-29.057	-12.914	3.229	-35.514	-17.736
lf_hur		0.000	-44.993	-24.968	-50.000	-69.961	-60.013	5.006	-79.974	-39.987	-29.974	-34.980	-55.007	-43.953
speed		0.000	1.976	7.502	0.161	5.880	-1.976	11.438	4.225	2.972	-3.904	-1.398	-1.333	2.361
rain_storm		0.000	22.357	25.758	21.479	14.024	27.960	29.439	11.160	26.280	25.514	23.762	22.530	22.791

GFDL HURRICANE MODEL DOWNSCALING

Means	A	B	C	D	E	F	G	H	I	J	K	L	M	N
ts	8.846	10.308	7.385	9.846	6.923	5.231	8.077	11.538	3.923	6.769	7.923	8.000	5.923	7.415
hur	5.538	7.654	5.231	7.077	4.654	2.962	5.846	8.769	2.231	4.500	6.346	5.808	3.769	5.196
mhurw	2.615	2.538	2.077	3.538	1.769	1.000	2.731	4.346	0.308	1.462	2.769	2.500	1.538	2.196
mhurw45	1.462	0.731	1.269	1.577	0.885	0.346	1.538	2.269	0.000	0.423	0.923	1.077	0.500	0.954
hur_w65	0.615	0.192	0.615	0.500	0.346	0.077	0.538	1.115	0.000	0.231	0.308	0.308	0.231	0.365
pdi	234.095	181.666	159.568	218.458	125.935	66.907	183.442	281.832	39.379	110.462	176.493	160.312	92.045	145.525
maxwnd	39.403	41.058	41.478	43.324	39.710	36.751	42.691	44.314	36.082	40.702	43.562	42.821	39.015	40.897
maxwnd_hur	49.069	46.102	45.374	50.508	45.734	40.434	46.507	50.075	38.112	47.204	48.222	48.428	45.911	46.115

% Change	A	B	C	D	E	F	G	H	I	J	K	L	M	N
ts		0.0	-28.357	-4.482	-32.839	-49.253	-21.643	11.932	-61.942	-34.333	-23.137	-22.390	-42.540	-28.066
hur		0.0	-31.657	-7.539	-39.195	-61.301	-23.622	14.568	-70.852	-41.207	-17.089	-24.118	-50.758	-32.114
mhurw		0.0	-18.164	39.401	-30.299	-60.599	7.604	71.237	-87.865	-42.396	9.102	-1.497	-39.401	-13.475
mhurw45		0.0	73.598	115.732	21.067	-52.668	110.397	210.397	-100.000	-42.134	26.265	47.332	-31.601	30.506
hur_w65		0.0	220.312	160.417	80.208	-59.896	180.208	480.729	-100.000	20.312	60.417	60.417	20.312	90.104
pdi		0.0	-12.164	20.253	-30.678	-63.170	0.978	55.138	-78.323	-39.195	-2.848	-11.755	-49.333	-19.894
maxwnd		0.0	1.023	5.519	-3.283	-10.490	3.977	7.930	-12.119	-0.867	6.099	4.294	-4.976	-0.392
maxwnd_hur		0.0	-1.579	9.557	-0.798	-12.294	0.878	8.618	-17.331	2.390	4.598	5.045	-0.414	0.028

variable key

name	description	units
ts	Tropical storm frequency (wind >= 17 m s^{-1})	no. per year
hur	Hurricane frequency (wind >= 33 m s^{-1})	no. per year
mhurw	Major hurricanes (wind >= 50 m s^{-1})	no. per year
mhurw45	Cat 4 & 5 hurricanes (wind >= 59 m s^{-1})	no. per year
hur_w65	Strong Cat 4+ hurricanes (wind >= 65 m s^{-1})	no. per year
pdi	Power Dissipation Index	1.0e9 (m**3/s**2)
maxwnd	Mean max wind	m/s

```
| maxwnd_hur       | Mean max wind (Hurricanes only)           | m/s
| lf_ts            | USA land fall (Tropical Storm & hurricane) | no. per year
| lf_hur           | USA land fall (Hurricanes)                | no. per year
| speed            | Mean translation speed of storm           | m/s
| rain_storm       | Average rain within 100 km of storm center |
|                        (Tropical storms and hurricanes)     | mm/day
+------------------+--------------------------------------------+--------------------+
```

Table 3. Storm statistics from CMIP5 vs CMIP3-based downscaling experiment results for Atlantic tropical storms and hurricanes. CMIP3 and CMIP5 refer to storm climates changes simulated using climate change information from the CMIP3 and CMIP5 multi-model ensembles. Control refers to the present-day climate simulations. The hurricane model results are for the average of runs using the two model versions (GFDL and GFDN).

Model Key:

A	--->	obs	
B	--->	atl_NCEP.bams	(CONTROL)
C	--->	atl_A1B_ens18	(CMIP3)
D	--->	atl_CMIP5_LATE	(CMIP5)

		Zetac Model			Hurricane Model		
Means	A	B	C	D	B	C	D
ts	9.000	11.259	8.185	8.704	10.852	7.926	8.222
hur	5.296	6.185	5.111	5.037	8.019	5.463	5.759
mhurw	2.370	0.000	0.000	0.000	2.704	2.241	2.278
mhurw45	1.370	0.000	0.000	0.000	0.574	1.074	0.796
hur_w65	0.519	0.000	0.000	0.000	0.111	0.389	0.204
pdi	235.216	179.116	140.806	137.459	183.054	151.618	146.287
maxwnd	38.805	34.112	35.124	35.049	41.359	41.083	42.032
maxwnd_hur	48.857	38.748	37.959	39.549	46.185	46.543	47.924
lf_ts	2.370	2.185	1.815	2.259			
lf_hur	1.037	0.963	0.741	0.852			
speed	6.817	6.440	6.551	6.247			
rain_storm		170.376	205.939	185.541			
rain_hur		272.09	335.20	311.06			

		Zetac Model			Hurricane Model		
% Change	A	B	C	D	B	C	D
ts		0.000	-27.303	-22.693	0.000	-26.963	-24.235
hur		0.000	-17.365	-18.561	0.000	-31.874	-28.183
mhurw		0.000	NaN	NaN	0.000	-17.123	-15.754
mhurw45		0.000	NaN	NaN	0.000	87.108	38.676
hur_w65		0.000	NaN	NaN	0.000	250.450	83.784
pdi		0.000	-21.388	-23.257	0.000	-17.173	-20.085
maxwnd		0.000	2.967	2.747	0.000	-0.667	1.627
maxwnd_hur		0.000	-2.036	2.067	0.000	0.775	3.765
lf_ts		0.000	-16.934	3.387			
lf_hur		0.000	-23.053	-11.527			
speed		0.000	1.724	-2.997			
rain_storm		0.000	20.873	8.901			
rain_hur		0.000	23.19	14.32			

variable key

name	description	units
ts	Tropical storm frequency (wind >= 17 m s^{-1})	no. per year
hur	Hurricane frequency (wind >= 33 m s^{-1})	no. per year
mhurw	Major hurricanes (wind >= 50 m s^{-1})	no. per year
mhurw45	Cat 4 & 5 hurricanes (wind >= 59 m s^{-1})	no. per year
hur_w65	Strong Cat 4+ hurricanes (wind >= 65 m s^{-1})	no. per year

```
| pdi              | Power Dissipation Index                    | 1.0e9 (m**3/s**2)
| maxwnd           | Mean max wind                              | m/s
| maxwnd_hur       | Mean max wind (Hurricanes only)            | m/s
| lf_ts            | USA land fall (Tropical Storm & hurricanes)| no. per year
| lf_hur           | USA land fall (Hurricanes)                 | no. per year
| speed            | Mean translation speed of storm            | m/s
| rain_storm       | Average rain within 100 km of storm center |
|                  |        (Tropical storms and hurricanes)    | mm/day
| rain_hur         | Average rain within 100 km of storm center |
|                  |        (Hurricanes only)                   | mm/day
+------------------+--------------------------------------------+-------------------+
```

Figure Captions

Fig. 1. Means (circles) and ranges (bars) across all simulated years of storm counts for each model experiment. Filled circles and triangles indicate where the change between the present day (Control) run and late 21st century (warm climate) frequency is statistically significant ($p=0.05$), according to a two-sample, one-sided t-test (filled circle) or a one-sided Mann-Whitney-Wilcoxon median test (triangles). "Odd Years" results refer to the 13 (Aug-Oct.) seasons simulated for the individual CMIP3 models. "All Years" results refer to the 27 (Aug.-Oct.) seasons simulated for the 18-model ensemble CMIP3 or CMIP5 climate changes. Results were obtained by downscaling using the Zetac regional model (a-c) or using the Zetac model followed by a second downscaling step applied to each storm case using the GFDL hurricane model (d-h). Results are shown for up to five classes of storm intensity: tropical storms and hurricanes (a,d); hurricanes (b,e); major hurricanes, category 3-5 (c,f); category 4-5 hurricanes (g); and strong category 4+ hurricanes with maximum winds exceeding 65 $m\ s^{-1}$(h). The GFDL model results (d-h) are based on a two-member ensemble for each case using two versions of the GFDL hurricane model (GFDL and GFDN). Major hurricanes from the Zetac model (c) are diagnosed using central pressure rather than maximum winds.

Fig. 2. As in Fig. 1 (d-h) but using a statistical model to refine the intensity projections from the Zetac 18-km grid regional model, rather than using a second dynamical downscaling step.

Fig. 3. Comparison of percent changes in frequency of (a) tropical storms and hurricanes, and (b) hurricanes, for the Zetac regional model experiments and the C180 global model projections for the late 21st century. Results are shown for the CMIP3/A1B and CMIP5/RCP4.5 multi-model ensembles and for 7 common individual model experiments from CMIP3/A1B. The gold lines depict the least squares best fit line through the seven scatterplot points for the seven common individual model experiments.

Fig. 4. Frequency histograms for maximum surface wind speeds (a,c in m s^{-1}) and minimum surface pressures (b,d in HPa) for observations (black dashed line), control run (atl_NCEP_bams; thick black), CMIP3/A1B multi-model ensemble (atl_A1B_ens18; thick red), and ten CMIP3/A1B individual models (see legend). All results are for the Zetac 18-km grid regional downscaling model (odd years only). Normalized histograms are shown in (c,d).

Fig. 5. As in Fig. 4 but for maximum surface wind speeds from the GFDL hurricane model downscaling experiments (ensemble of GFDL and GFDN versions). Results shown for observations (black dashed line), control run (atl_NCEP_bams/GFDLe; thick black), CMIP3/A1B multi-model ensemble (atl_A1B_ens18/GFDLe; thick red), and the ten CMIP3/A1B individual models (see legend). Histograms (a) and normalized histograms (b) are shown.

Fig. 6. As in Fig. 4 but for GFDL hurricane model downscaling experiments based on the CMIP3/A1B and CMIP5/RCP4.5 ensemble mean climate changes. The ensemble of the GFDL and GFDN versions are shown, using all 27 years (1980-2006) for the control and perturbed samples. Results are shown for the control run (atl_NCEP_bams/GFDLe; black), CMIP3/A1B multi-model ensemble (atl_A1B_ens18/GFDLe; red), and CMIP5/RCP4.5 multi-model ensemble (atl_CMIP5_LATE/GFDLe; blue). Histograms (a,b) and normalized histograms (c,d) are shown.

Fig. 7. Tracks and intensities of all storms reaching category 4 or 5 intensity (>=59 m s^{-1}) in the GFDL hurricane model downscaling experiments, using model versions GFDL (a-c) or GFDN (d-f). Results shown for the control climate (a,d); CMIP3/A1B multi-model ensemble climate change (b,e); and CMIP5/RCP4.5 multi-model ensemble climate change (c,f).

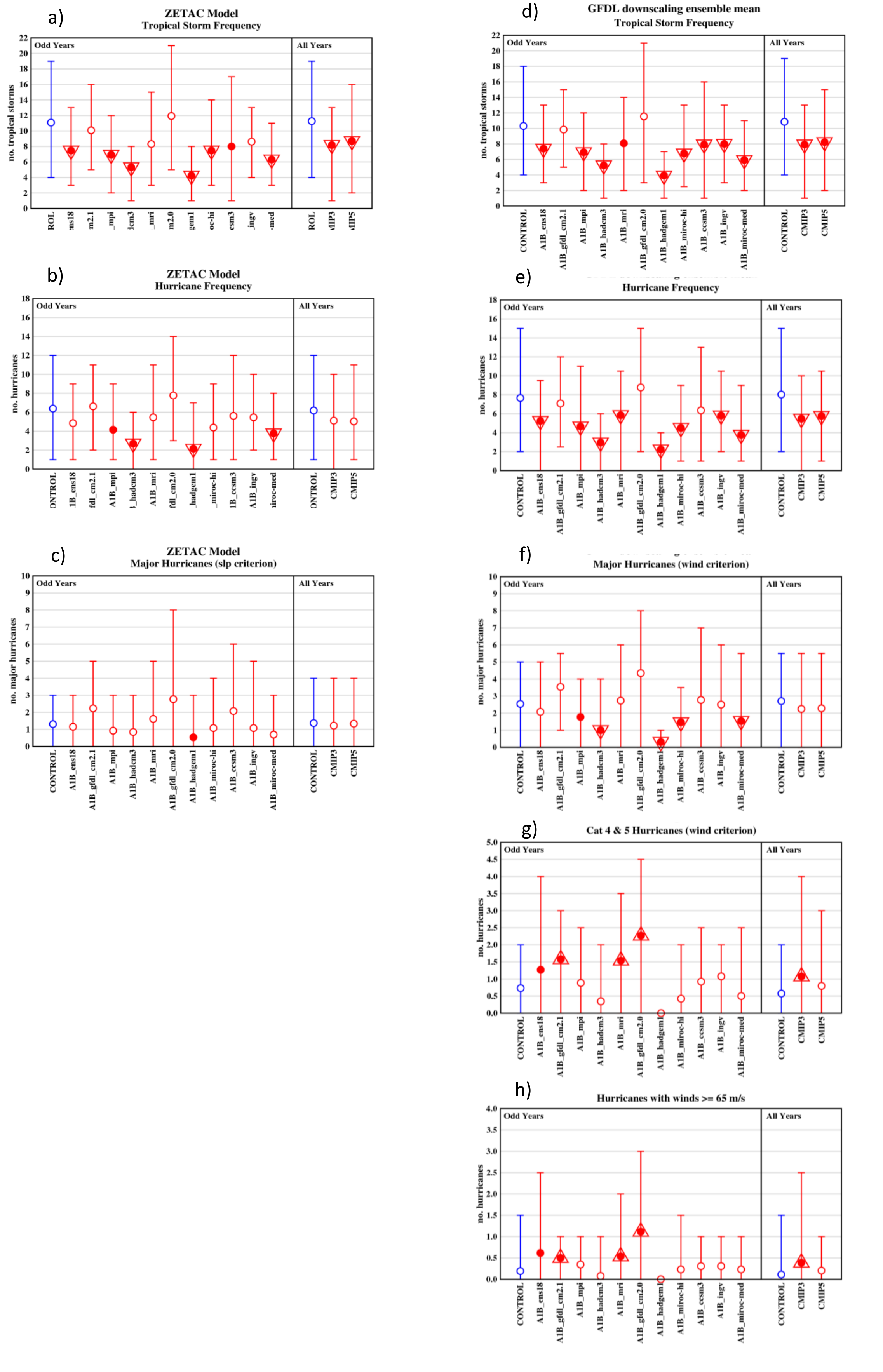
Fig. 8. Geographical distribution of the rate of occurrence (a-c) or change in rate of occurrence (d-e) of Category 4-5 storms for control (a), CMIP3/A1B ensemble (b,d), or CMIP5/RCP4.5 ensemble (c,e). Shown are the combined results obtained using the GFDL and GFDN versions of the GFDL hurricane model and are scaled as storm counts per decade.

Fig. 9. (a) As in Fig. 1 except for rain rate averaged within 100 km of the storm center and averaged over all tropical storm and hurricane periods [mm day^{-1}]. (b) Change [%]

between the control to warm climate in average hurricane rainfall rate for various averaging radii about the storm center [km] for the CMIP3/A1B (black) and CMIP5/RCP4.5 (red) ensembles. The dashed lines are an idealized water vapor content scaling, based on multiplying the average SST change in the region 10-25^{o}N, 20-80^{o}W by 7% per degree Celsius.

Fig. 10. Comparison of published dynamical model projections of Atlantic basin tropical storm frequency changes versus the statistical downscaling model of Villarini et al. (2011), which is based on relative SST changes. The figure shows that in most cases where the dynamical models projected increased tropical storm frequency, those models were usually being forced with or had internally computed SST warming the tropical Atlantic that exceeded the tropical mean.

Fig. 1



a)
ZETAC Model
Tropical Storm Frequency
b)
ZETAC Model
Hurricane Frequency
c)
ZETAC Model
Major Hurricanes (slp criterion)
d)
GFDL downscaling ensemble mean
Tropical Storm Frequency
e)
Hurricane Frequency
f)
Major Hurricanes (wind criterion)
g)
Cat 4 & 5 Hurricanes (wind criterion)
h)
Hurricanes with winds >= 65 m/s
Odd Years
All Years
no. tropical storms
no. hurricanes
no. major hurricanes
CONTROL
A1B_ens18
A1B_gfdl_cm2.1
A1B_mpi
A1B_hadcm3
A1B_mri
A1B_gfdl_cm2.0
A1B_hadgem1
A1B_miroc-hi
A1B_ccsm3
A1B_ingv
A1B_miroc-med
CMIP3
CMIP5

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Fig. 2

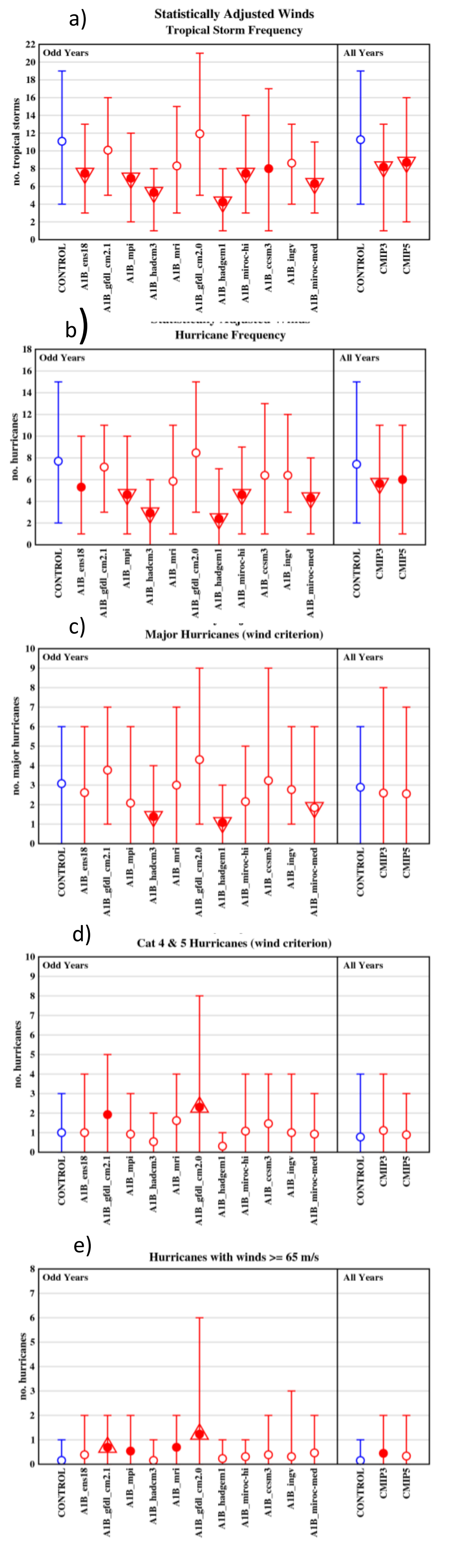

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Fig. 3

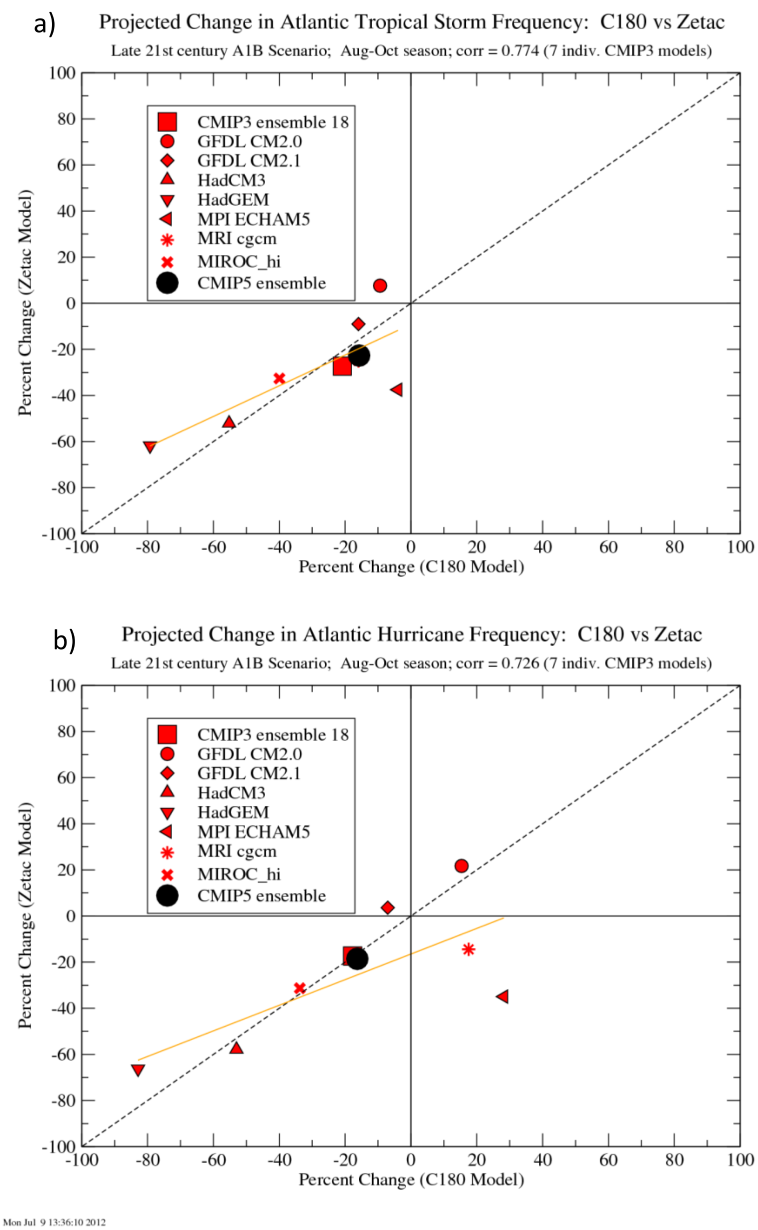

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Fig. 4

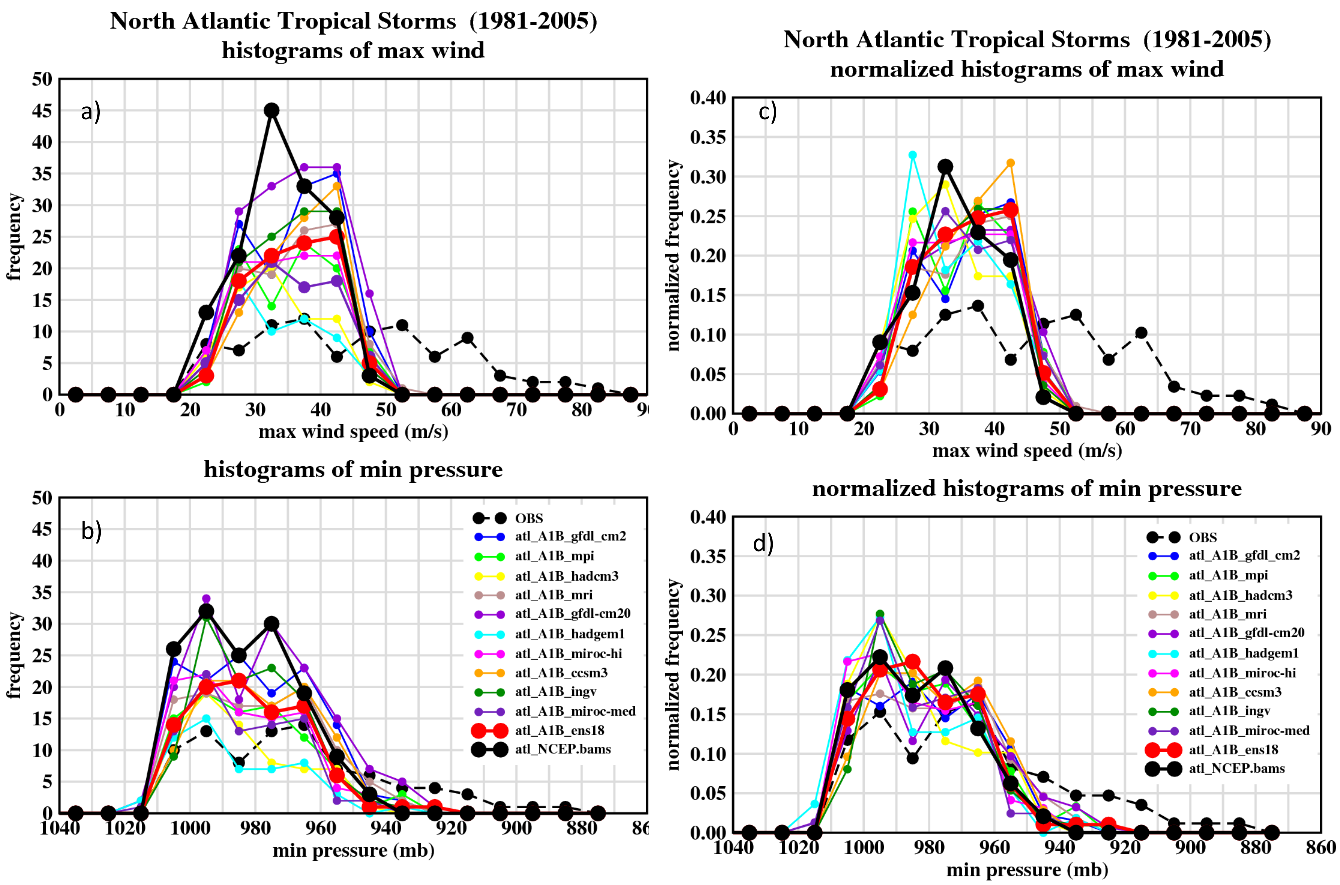

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Fig. 5

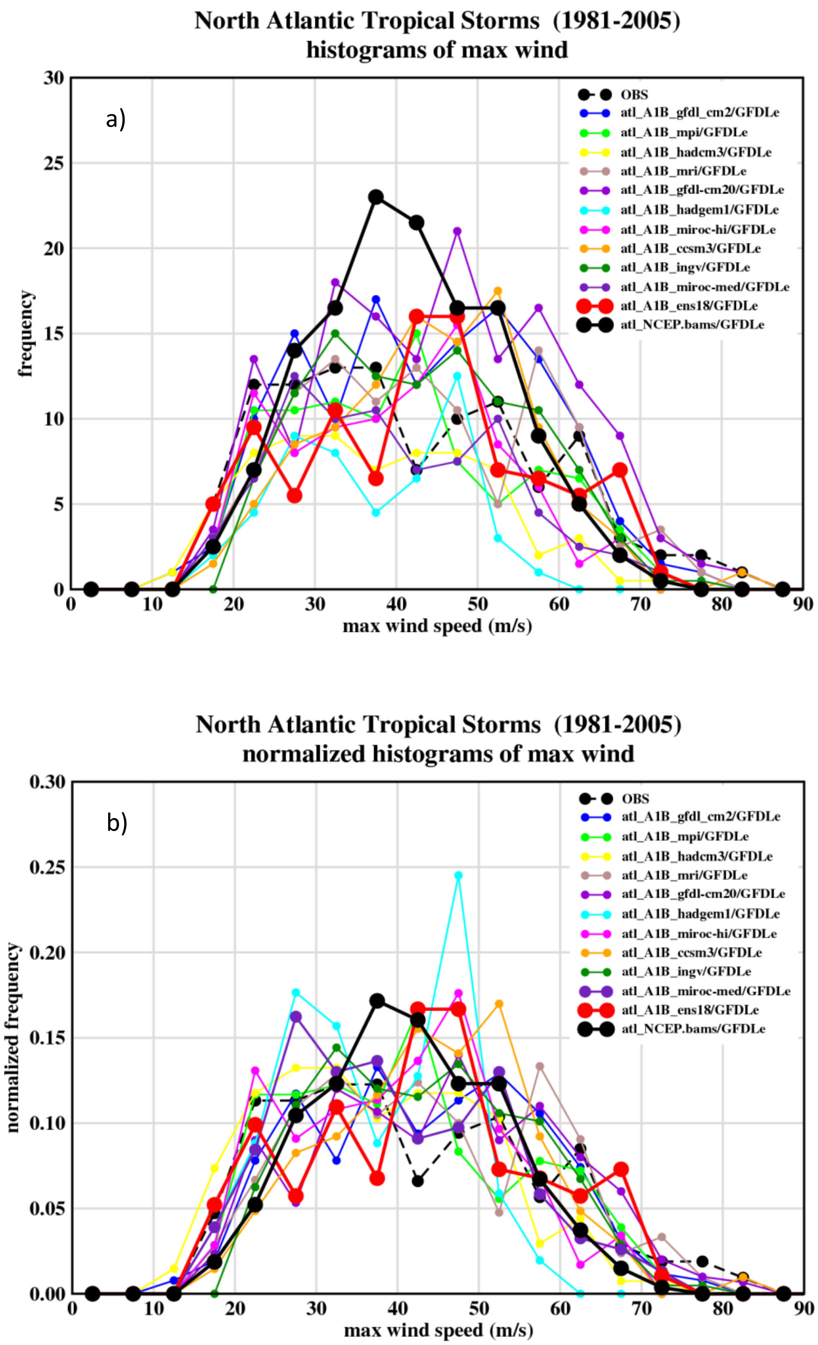

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Fig. 6

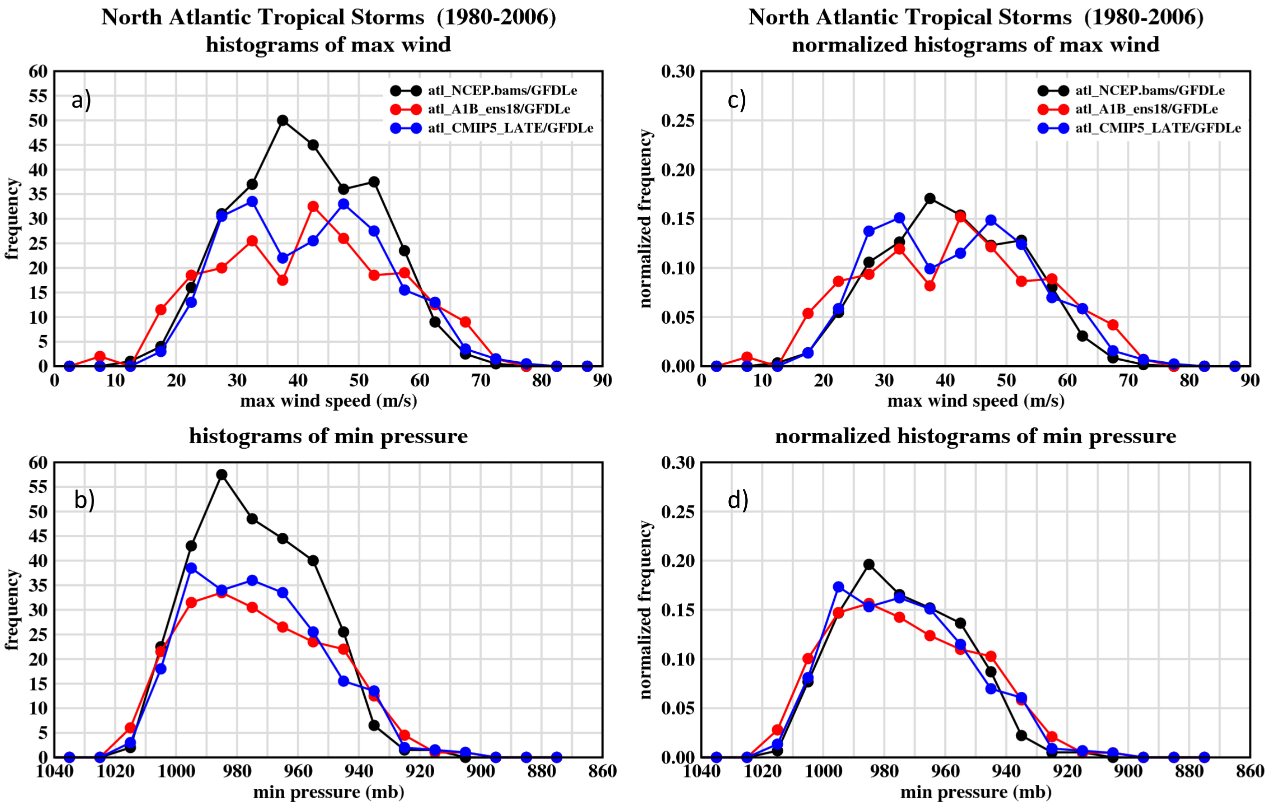

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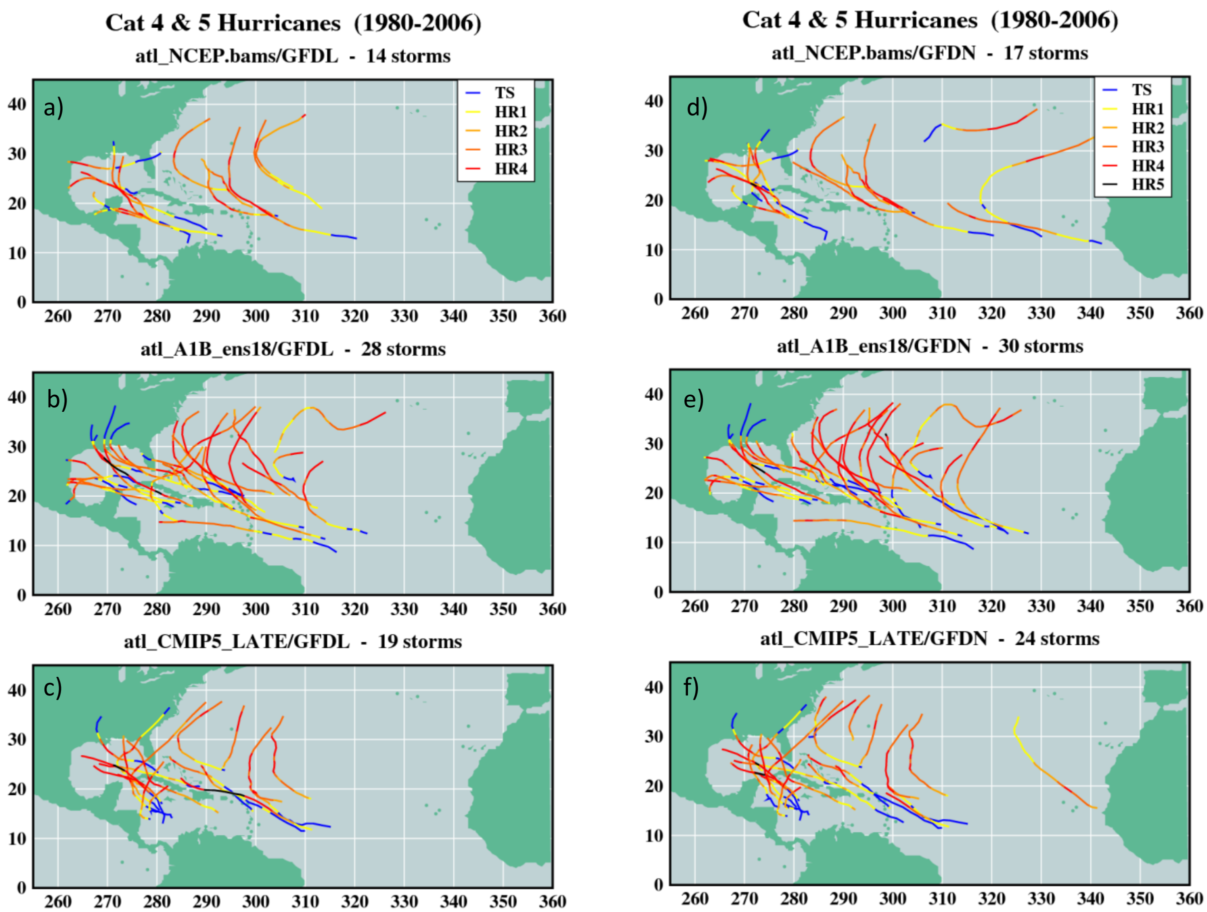
Fig. 7



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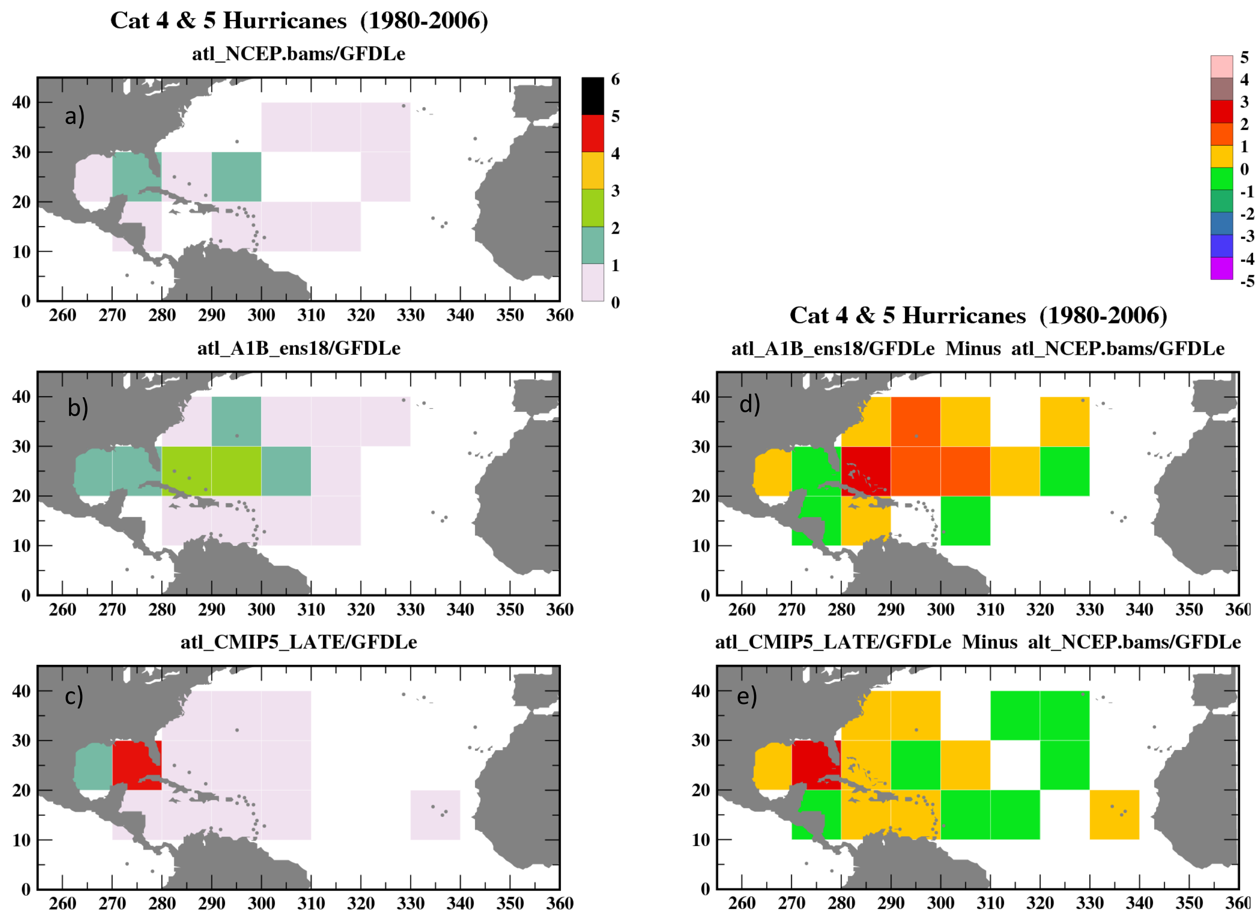

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Fig. 9

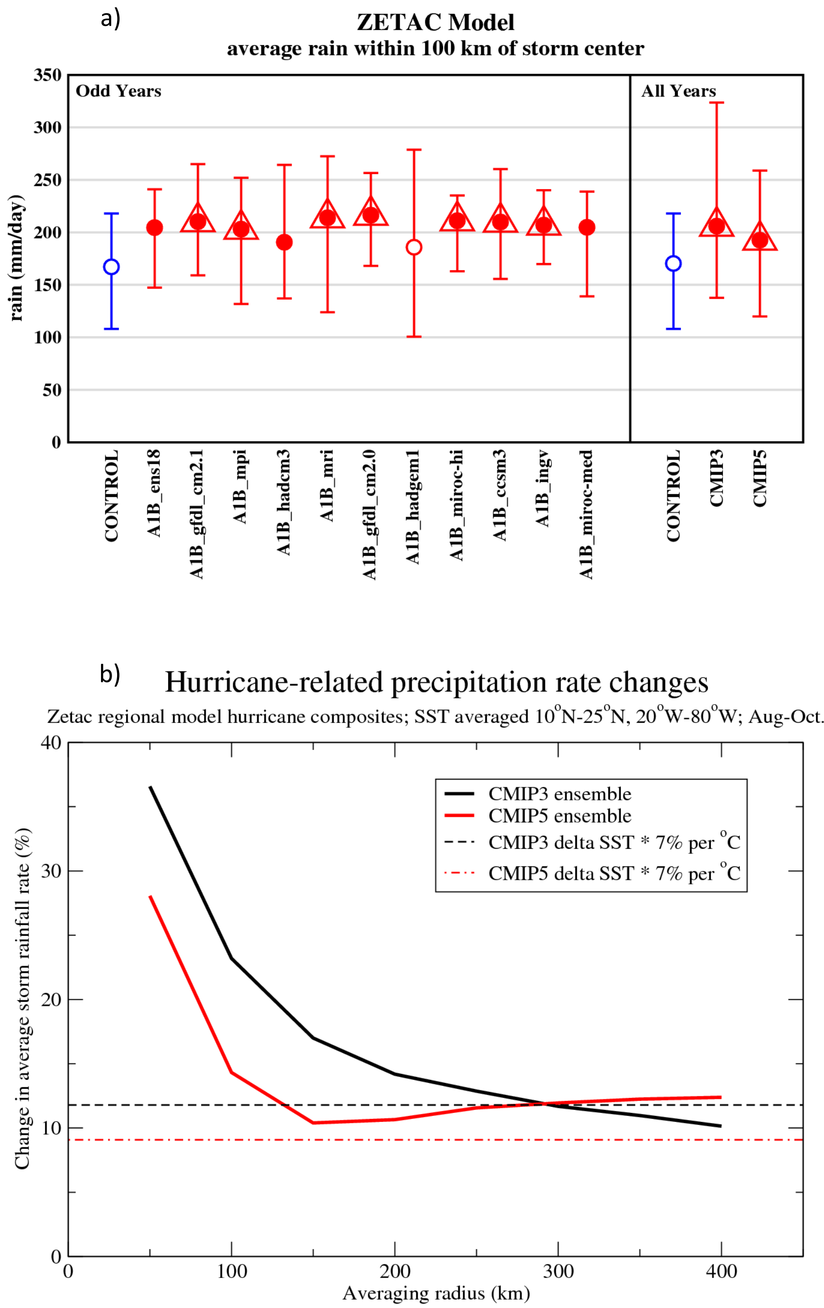

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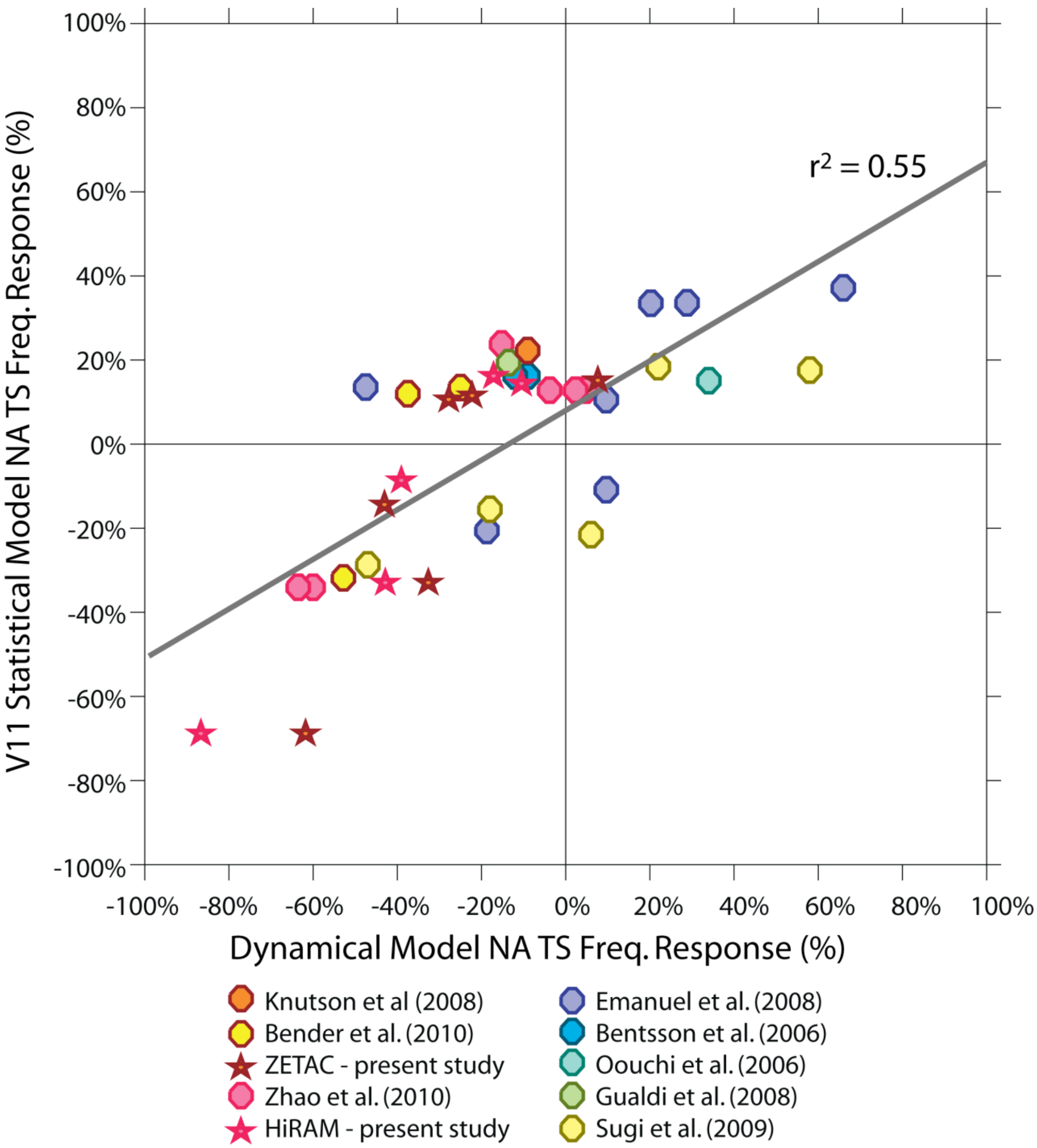
Fig. 10



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